Photon acceleration in variable ultra-relativistic outflows and high-energy spectra of Gamma-Ray Bursts.

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ABSTRACT

MeV seed photons produced in shocks in a variable ultra-relativistic outflow gain energy by the Fermi mechanism, because the photons Compton scatter off relativistically colliding shells. The Fermi-modified high-energy photon spectrum has a non-universal slope and a universal cutoff. A significant increase in the total radiative efficiency is possible. In some gamma ray bursts, most of the power might be emitted at the high-energy cutoff for this mechanism, which would be close to 100 MeV for outflows with a mean bulk Lorentz factor of 100.

Subject headings: Gamma-rays: Bursts — Radiation Mechanisms

1. Introduction

The most common model of gamma-ray burst (GRB) sources involves a relativistic outflow in which shocks occur and radiate away a fraction of the bulk kinetic energy. For typical model parameters the synchrotron emission peaks around 1 keV in the comoving frame, or ~ 100 keV in the observer frame. Generally, this is considered to be the primary spectrum observed. However, in internal shocks in the neighborhood of the flow photosphere, and also in external shocks in some cases (e.g. Madau, Blandford, & Rees 2000), the shocks can have a non-negligible Thomson scattering depth, which results in upscattering of these primary photons. Single scattering on individual shock-accelerated electrons with Lorentz factors $\gamma_e \sim 300$ produces photons with energies $\sim \gamma_e^2$ keV in the comoving, or $\sim \Gamma\gamma_e^2 \sim 10\Gamma_2$ GeV in the observer frame, where $\Gamma = 100\Gamma_2$ is the bulk Lorentz factor.

Here we concentrate on a different, multiple scattering component. This is associated with mildly relativistic motions of different ejecta shells or turbulent cells resulting from multiple shock interactions, which contain more energy than the shock-accelerated highly relativistic electrons. Multiple interacting shells are naturally expected in internal shocks, and also in external shocks when a longer lasting modulated outflow runs into the first decelerated shell (e.g. Fenimore & Ramirez-Ruiz 2000; Kumar & Piran 2000).

Repeated scatterings using the energy of these bulk motions boost the photon energy through the equivalent of the Fermi acceleration mechanism of particles (Blandford & Payne 1981). This is related to Thompson's (1994) photon scattering off Alvfén waves, but our mechanism relies instead on relative bulk motions. It differs also in using synchrotron photons instead of thermal photons as its source term, and hence leads to different characteristic energies. This bulk Comptonization results in a spectrum extending at least up to $\sim$ MeV in the comoving frame and $\sim 100\Gamma_2$ MeV in the observer frame. The spectral power or luminosity per decade can increase as steeply as linearly in the photon energy. This provides a natural explanation for those GRB spectra (e.g. Preece et al 1999) which show a positive νF_ν slope above the MeV range (generally $\leq +1$), which cannot be explained by direct synchrotron radiation from Fermi shock-accelerated electrons.

The component made up of bulk-scattered photons can extend up to a maximum observed energy $\sim 100\Gamma_2$ MeV. Beyond this energy, Klein-Nishina and electron recoil effects set in, and the spectrum reverts to being dominated by the seed spectrum (with negative or flat power law slope) of the unscattered photons above the synchrotron peak.

In this work we adopt a test photon model, which assumes no back reaction on the plasma. Several potentially important effects are neglected (upscattered photons can heat electrons in the colliding shells and produce pairs, light pressure ensures that the total comoving energy of the scattered photons cannot exceed the total kinetic energy of the relative shell motions). These effects will be investigated elswehere (Gruzinov, Mészáros , & Rees 2000). The simplified approach that we use here retains the essential properties of the bulk motion comptonization phenomenon, and allows us to explore the main qualitative features it introduces in the spectra.

In §2 we specify the GRB model, in §3 we give an analytical model of Fermi acceleration of photons by colliding shell, and in §4 we describe our Monte Carlo simulations. The results are discussed and related to current and future observations in §5.

2. The GRB internal shock model

As a specific example to illustrate the effect, we restrict ourselves here to the internal shock model. We use a standard set of parameters for the ultra-relativistic outflow model of GRBs (e.g. Mészáros & Rees 2000), i.e. luminosity $L = 10^{52} L_{52}$ erg/s, $L_{52} \sim 1$; terminal Lorentz factor $\Gamma \sim 100$; variability time scale $t_v = 10^{-3} t_{ms}$ s, with $t_{ms} \sim 1$. With these parameters the shock between shells ejected at typical time intervals t_v with $\Delta\Gamma \sim \Gamma$ occurs at a radius $R \sim \Gamma^2 c t_v$. To determine the optical depth to Thomson scattering, we estimate the proper density of the wind as

$$n \sim \frac{L}{4\pi R^2 \Gamma^2 m_p c^3}. \tag{1}$$

The proper radial width of colliding shells is $\sim R/\Gamma$, and the optical depth is

$$\tau \;\sim\; n\sigma_T R/\Gamma \;\sim\; \frac{L_{52}}{t_{ms}}\left(\frac{200}{\Gamma}\right)^5 . \tag{2}$$

We see that optical depths of $\gtrsim 0.1$ are natural. In fact, values of $\tau \sim 1$ are not purely coincidental, since in the standard GRB model the parameters are chosen so as to make $\tau < 1$ enabling a non-thermal spectrum, and the "preferred" model uses smaller values of Γ (which do not require overly low baryon loads), thus making $\tau \lesssim 1$. The observational fits to the models provide reasonable support for such a choice of parameters (e.g. van Paradijs, Kouveliotou & Wijers, 2000).

Most of the seed photons are emitted at the synchrotron peak. Assuming mildly relativistic internal shocks, and magnetic field and electron energies equal to a fraction ξ_B and ξ_e of their equipartition values, the synchrotron peak frequency in the comoving frame is

$$h\nu \;\sim\; \left(\frac{\xi_e}{0.1}\right)^2 \left(\frac{\xi_B}{0.1}\right)^{1/2} \frac{L_{52}^{1/2}}{t_{ms}} \left(\frac{200}{\Gamma}\right)^3 \mathrm{keV}. \tag{3}$$

3. Analytical model of photon acceleration by colliding shells

The basic features of the bulk Comptonization process can be understood by means of a simple analytical model, which reproduces the essence of the Monte Carlo simulation discussed in §4. This model is sufficient to show that the high-energy slope of νF_ν can be positive, and gives a value for the cut off energy.

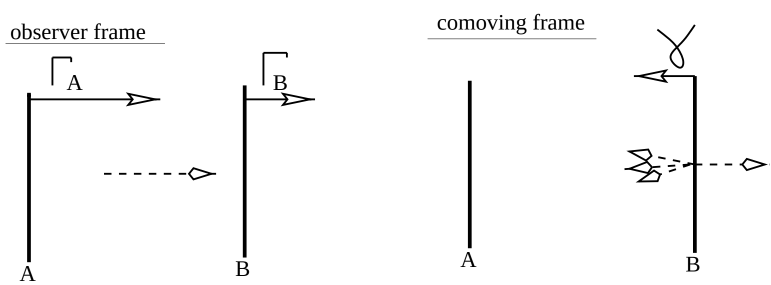

Fig. 1.— A photon scatters off relativistically colliding shells. As seen by shell A, the scattered photon has a small angle of incidence.

Consider a photon between two shells of equal optical depth $\tau \ll 1$ (Figure 1). The shells collide with an ultra-relativistic relative Lorentz factor $\gamma \gg 1$ [1]. Initially, in the frame comoving with shell B, the photon frequency is ν and the incidence angle is 0. We assume the Thomson regime, $h\nu \ll m_e c^2$. The probability that the photon passes through shell B without scattering is

[1] $\gamma = \frac{1}{2}\left(\frac{\Gamma_A}{\Gamma_B} + \frac{\Gamma_B}{\Gamma_A}\right)$. The case of $\gamma \sim 1$ requires a more cumbersome analysis. At our accuracy, we just assume that the ultra-relativistic solution is a useful approximation in the mildly relativistic regime.

$1-\tau$. The photon scatters forward with probability $\tau/2$, and it scatters backward with probability $\tau/2$. In the frame comoving with shell A, the backward scattered photon has a small incidence angle. The average (over the scattering kernel) of the Lorentz-transformed frequency is

$$\langle\nu\rangle \;=\; \frac{\int_{\pi/2}^{\pi} d\theta \sin\theta(1+\cos^2\theta)(1-\cos\theta)}{\int_{\pi/2}^{\pi} d\theta \sin\theta(1+\cos^2\theta)}\,\gamma\nu \;=\; \frac{25}{16}\,\gamma\nu\ . \tag{4}$$

Thus, after one scattering the total energy of photons is changed by a factor of $(25/32)\tau\gamma$, and the frequency is changed by a factor of $(25/16)\gamma$. Then the observed spectrum is a power law with the luminosity per frequency octave $\nu F_\nu \propto \nu^\beta$, with

$$\beta = \frac{\log(25\tau\gamma/32)}{\log(25\gamma/16)}\ . \tag{5}$$

The slope is positive if $\tau\gamma > 1.28$. The steepest slope is $\beta = 1$, which is achieved in the limit $\gamma \gg \tau^{-1}$. This model is similar to that for the ultrarelativistic isotropic multiple scattering (c.f. Rybicki & Lightman 1979, p. 212) where the slope is $\beta = 1 + \log(\tau')/\log(\gamma'^2)$. In the last equation we should use $\tau' \sim \tau$ and $\gamma' = \sqrt{(1+\gamma)/2}$, which is the Lorentz factor of the colliding shells in the center of mass frame.

A finite convergence time of the two geometrically thin shells does not introduce a limit on the maximum photon energy, as can be seen from the equivalent of Zeno's paradox (since the photons always travel faster than the shells approach, the number of photon reflections can in principle grow arbitrarily large for a shrinking separation). However, the effective number of scatterings should be limited, introducing a corresponding spectral cut off at high energies, due to (i) a gradual Klein-Nishina decline of the cross section; (ii) a sharp cut-off of the energy of scattered photons due to electron recoil (the maximal energy of a photon backward scattered from shell B observed in frame A is $\gamma m_e c^2$); (iii) radiation pressure back reaction effects (if $\beta > 0$, the total energy of the scattered photons builds up and the photon pressure can prevent the collision of the shells).

4. Monte Carlo simulations

Monte Carlo simulations of the photon acceleration model sketched in Figure 1 were performed in order to check the simple estimates of §3. These confirm that the analytical results, including equation (5), are a useful approximation in the mildly relativistic regime. They also allow us to find in more detail the shape of the Compton recoil / Klein-Nishina cut off (see Figure 2). The Monte Carlo simulations were done using two approximations, which simplify the problem without affecting significantly the result: polarization effects are neglected, and multiple scattering during one passage through a shell is neglected.

Initially, a seed synchrotron spectrum is released. The seed spectrum is isotropic in the center of mass frame, rising at low energies ($\beta = 4/3$), with a smooth transition to a spectrum decreasing at high energies (where we take as an example $\beta = -0.5$).

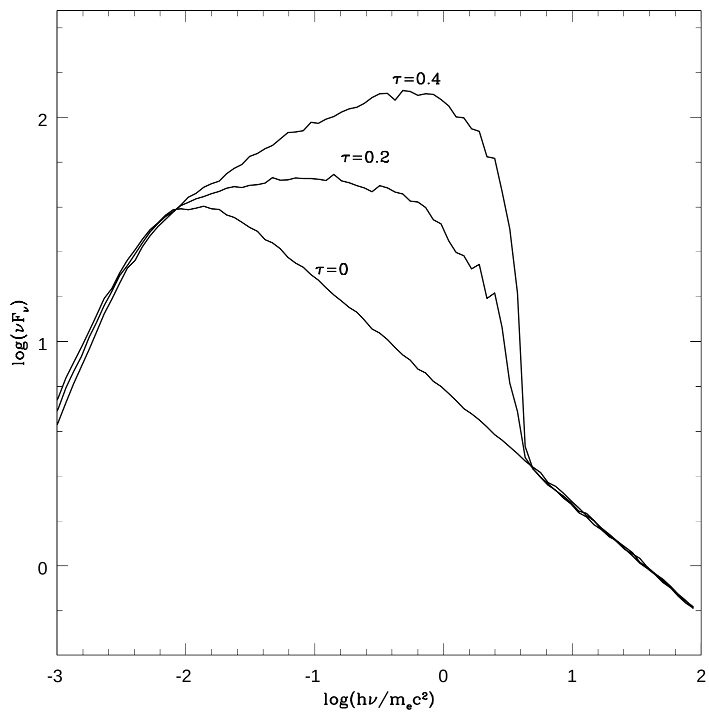

Fig. 2.— Monte Carlo simulations of bulk Comptonization between two converging slabs (relative Lorentz factor $\gamma = 5$), showing the comoving flux per logarithmic photon energy interval for three different optical depths τ. The observed spectrum is the same multiplied by the mean bulk Lorentz factor $\Gamma = 10^2\Gamma_2$.

In Figure 2 we show a spectral calculation for two shells similar to those of Figure 1, using a relative Lorentz factor $\gamma = 5$. The unscattered seed synchrotron spectrum is marked "$\tau = 0$". The spectrum of all photons that finally escape outwards (to the right) through the shell B, as measured in the (comoving) frame B, is shown in Figure 2 for different values of τ. The Compton recoil / Klein-Nishina effects are noticeable at about 1 MeV comoving energies, and there is a sharp Compton recoil cut off at $h\nu/(m_e c^2) = \gamma$. In the observer frame this spectrum would be blueshifted by the factor Γ_B.

The dependence on the relative Lorentz factor is illustrated in Figure 3, showing the effect for a fiducial relative Lorentz factor $\gamma = 2$, which may also be characteristic of the reverse shock in an external deceleration shock scenario. As expected, the steepening remains present but becomes less strong as weaker shocks are considered. The cut-off, however, is inherent to the scattering physics, and although it has a tendency to decrease somewhat with decreasing γ, its order of magnitude remains in the neighborhood of $h\nu \sim m_e c^2 \sim 1$ MeV (comoving frame).

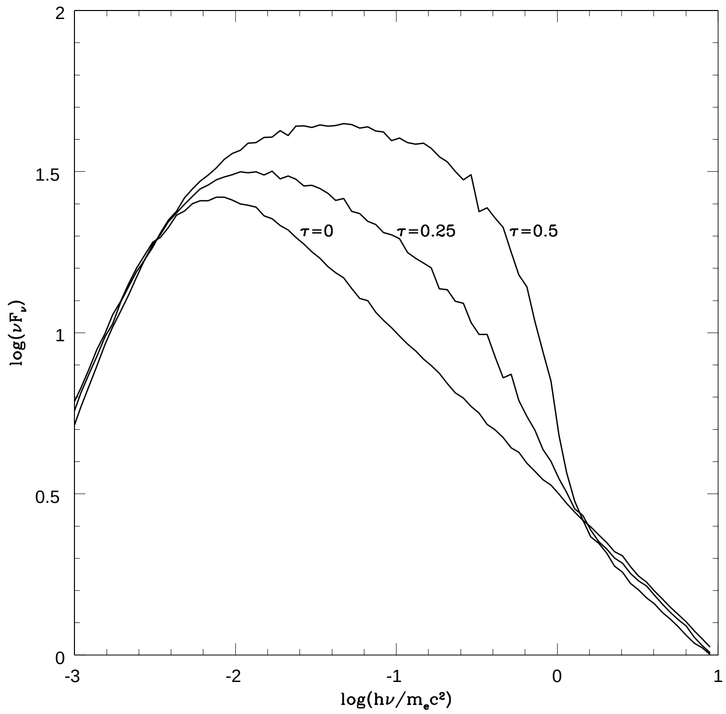

Fig. 3.— Same as figure 2, comoving frame spectrum for a case with $\gamma = 2$.

5. Discussion

The Fermi acceleration of photons in the standard GRB fireball model has several consequences of theoretical and observational interest. The first is that it can naturally produce νF_ν spectra which are harder than the input synchrotron spectrum, including the possibility of an increasing νF_ν above the usual break found in the Band parameterization of spectra (Band et al 1999, Preece et al 1999). The latter is a property that is hard to obtain with a synchrotron model. Such rising $\nu F_\nu \propto \nu^\beta$ are expected, in this model, to have $\beta \lesssim 1$, and this implies that in some GRB most of the energy is at energies $h\nu \sim 100(\Gamma/10^2)$ MeV, well above the BATSE instrument band on the Compton Gamma Ray Observatory (CGRO). The current observational situation is that BATSE finds approximately 16 % of the spectra to be rising at $\gtrsim 1$ MeV, and the observed rise is not faster than $\beta = 1$ (Preece et al 1999). These fits generally cut off above 1.8 MeV, and the break is usually not much lower than this, so there is some uncertainty. The COMPTEL instrument on CGRO, sensitive up to 30 MeV, has analyzed ~ 30 bursts (Schoenfelder et al 2000), and an analysis of the slopes indicates in several cases νF_ν slopes $\beta \sim 0$, with one burst of $\beta \sim 0.5$ (Kippen et al 1999). The EGRET experiment on CGRO has detected ~ 30 bursts with the scintillation counters in the 1-200 MeV range, and ~ 7 bursts with the spark chambers in the 100 MeV-30 GeV range. In this range the spectra are largely noise-dominated (Schaefer et al 1998, Bromm & Schaefer 1999).

However, the scintillation spectral slopes (Catelli, Dingus & Schneid, 1997) are compatible with $\beta \lesssim 0$, although some could be positive and others negative, which is compatible with the analysis of spark chamber data (e.g. Sommers, 1994; Hurley et al, 1994). Large area detectors such as GLAST should be able to obtain more definite answers in the 20 MeV-300 GeV range.

Another implication of the photon acceleration described here is that it provides a natural mechanism to increase the efficiency of conversion of baryon bulk motion into photon energy. This is of interest since in general the internal shock synchrotron efficiency for radiating in the BATSE band is limited to 1-10% (Kumar 2000; Spada, Panaitescu & Mészáros 2000; see however Fenimore & Ramirez-Ruiz 2000, and observation-based estimates by Freedman & Waxman 2000). The increase in the radiative efficiency is simply given by the increase in the value of νF_ν at different energies, or by the integral $\int F_\nu d\nu$ in the range of interest. In the generic examples shown, this increase is substantial. Of course, the spectra shown in Figures 2 and 3 are test photon spectra, which do not take into account the back-reaction of radiation. The latter can become important when a substantial fraction of the bulk energy has been converted to radiation through Fermi acceleration, and the natural limit for this effect can be estimated as $\sim 50\%$ radiative efficiency.

The calculations presented here are meant to illustrate the consequences of photon acceleration by bulk motions. A self-consistent calculation is needed in order to explore the back-reaction of the radiation pressure and pair formation on the shell dynamics. Pair formation has an angle averaged cross section $\sigma_{\gamma\gamma} \sim \sigma_T/8$ at a threshold which is similar to that for Klein-Nishina effects. It is not very important in low compactness situations (shocks at large radii), while in high compactness cases the exponential tail of the photon distribution would lead to a pair cascade, which lowers the cut off in the comoving spectra of Figures 2,3 to $\lesssim 0.5$ MeV, possibly with some pile-up of photons at this energy (Gruzinov, Mészáros & Rees, 2000).

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